LLNL-CONF-676358

LAWRENCE LIVERMORE NATIONAL LABORATORY

Categorization and Review of Existing Micro-mirror Array Technologies

J. B. Hopkins, R. M. Panas, Y. Song

August 18, 2015

American Society of Precision Engineering Annual Conference
Austin, TX, United States
November 1, 2015 through November 6, 2015

Categorization and Review of Existing Micro-mirror Array Technologies

Jonathan B. Hopkins[1a], Robert M. Panas[1b], and Yuanping Song[a]
[a]Mechanical and Aerospace Engineering
University of California, Los Angeles
Los Angeles, CA, USA
[b]Materials Engineering Division
Lawrence Livermore National Lab
Livermore, CA, USA

ABSTRACT
The aim of this paper is to categorize and compare the performance of existing two-dimensional (2D) micro-mirror array (MMA) devices and to establish physical bounds on the performance of such technologies. Existing MMA technologies are categorized according to their actuation approach and key examples are discussed to demonstrate how each category achieves their specific combinations of performance capabilities. Performance plots are provided that compare a variety of mirror-array-capability metrics such as mechanical half-range, maximum acceleration or stepping rate, and energy density. Considerations of mirror size, array size, and fill-factor are also addressed. The performance of an MMA design created by the authors will be included within these plots to highlight its unique advanced capabilities.

MICRO-MIRROR REVIEW EFFORT
The published performance capabilities of existing micro-mirror designs have been studied and compared for the purposes of this paper. Figure 1 provides a plot of the number of micro-mirror design publications per year since their conception.

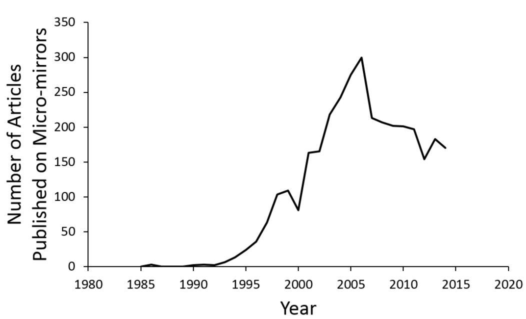

FIGURE 1. MMA publications over time

In this paper, we restrain our focus on 2D MMA designs that achieve at least tip and tilt DOFs. 87 designs from 22 companies and 21 academic research groups have been categorized and compared. The reported performance specs of each design have been adapted to a form that can be compared universally for all mirror designs. The performance of other micro-mirror designs will be discussed in a later paper.

MICRO-MIRROR ARRAY CATEGORIZATION
We primarily categorize 2D MMAs according to how they are actuated. We further differentiate these arrays by categorizing them according to whether their mirror surfaces are discrete or continuous (i.e., whether each mirror in the array is an independent well-defined unit or whether each mirror is ambiguously defined as a small portion of one continuous surface that is deformed by a multiplicity of actuators). We have thus divided the designs into eight categories: Plate Discrete, Comb Discrete, Thermal Discrete, Lorentz Discrete, Piezo Discrete, Plate Continuous, Piezo Continuous, and Lorentz Continuous.

1) Plate Discrete Actuation
Electrostatic plate actuators are most commonly used within discrete MMAs because they are compact, fast, require low power consumption, and are easily integrated within MEMS devices. More than 35 designs utilize electrostatic plate actuators from among the complete body of discrete 2D MMA designs that we considered in this study accounting for more than 60% of the designs.

Tip-Tilt-Piston Deformable Mirror (TTP-DM) [1], [2], developed by Boston Micromachines in 2007, consists of hexagonal mirrors with 3 DOFs (tip, tilt, and piston). Figure 2 illustrates the architecture of TTP-DM device. Each mirror is actuated by three independent pairs of electrostatic plates from below enabling 6 mrad (0.35˚) of tip or tilt motion and 2um of piston

[1]These are both first authors as their contributions to this paper are equal

stroke. The high fill-factor (99%), fast time response (17us), and high resolution (14 bits) make TTP-DM ideal for applications in wavefront control. TTP-DM's relatively small range of motion, however, limits its ability to steer light.

Transparent Networks Inc. (currently defunct) developed an MMA with ±10˚ tip and tilt range capability [3, 4]. Figure 3a is a cutaway of the device showing the layered structure. Each mirror connects to a mechanical angular amplifier which is actuated by electrostatic electrodes (Fig. 3b). The mechanical linkage is designed so that the rotation of the mirror is amplified by a factor of 4. The fill-factor is about 75%, but, in principle, this metric could be improved.

Other Plate Discrete 2D MMA designs of note can be found in [6-8] (by commercial companies) and [9-12] (by academic research groups).

2) Comb Discrete Actuation

Comb actuators are another form of capacitive actuation that utilize electrostatic force. The interdigitated teeth of the comb allow higher energy density and larger actuation forces than capacitive parallel plate actuators of the same size. However, the complex geometry of comb actuators increases the design and fabrication complexity of MMAs and thus makes their realization more challenging. About 25% of all discrete 2D MMA designs considered for this paper are classified as Comb Discrete designs.

Alcatel-Lucent developed a 2D tip-tilt-piston MMA actuated by electrostatic combs [13]. Figure 4a shows the mirror structure. The mirror surface is connected to four arms by flexible joints. Each arm is attached to a rotational comb (Fig. 4b). By controlling the voltage on each comb drive, the mirror surface can achieve up to ±4˚ tip/tilt and 5um upward piston motion within 20us time. The reported performance of this design is one of the best among all the 2D MMA devices.

IW Jung et al. [14] from Stanford University developed a comb-actuated MMA design that achieves up to ±0.9˚ tilt, ±0.1˚ tip, 0.07um piston, 99% fill-factor and ~10us response time. Figure 5a shows a top view and Fig. 5b shows a bottom view of the gimbaled structure of the mirror. Although not yet demonstrated, IW Jung et al. report that high fill-factor (>94%), fast response (<100us), and large rotational angle (>±10˚) are feasible for designs with appropriately scaled actuators.

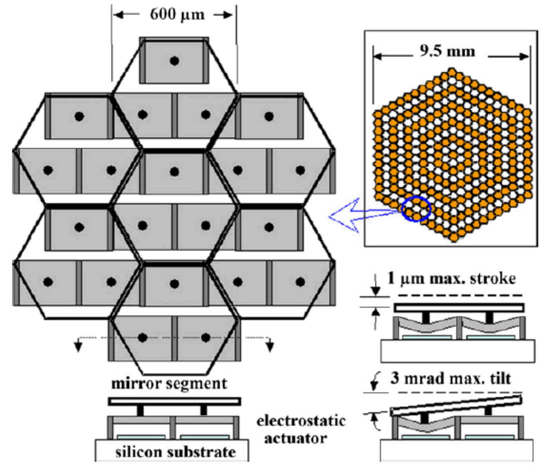

FIGURE 2. Top and side view of TTP-DM

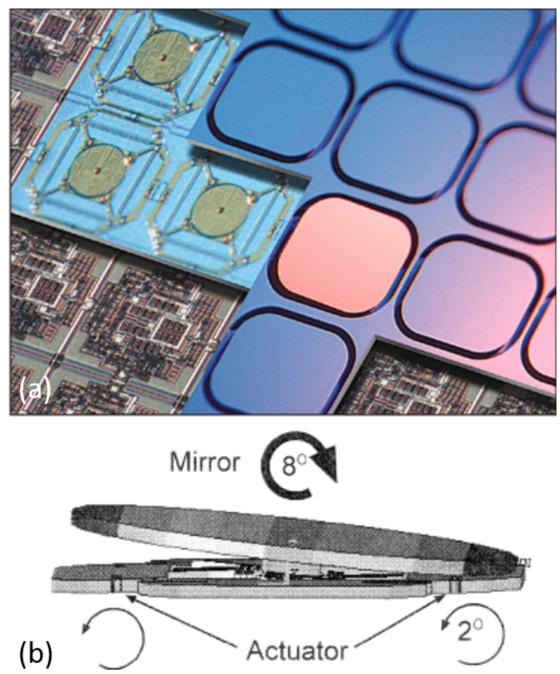

FIGURE 3. Transparent Networks MMA

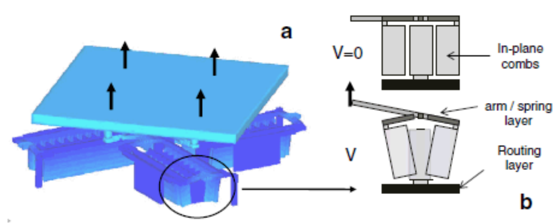

FIGURE 4. Alcatel-Lucent micro-mirror design

We have also created a Comb Discrete 2D MMA design [15, 16]. The predicted performance capabilities of our array are discussed and compared in Performance Plots Section. Other Comb Discrete MMA designs of note can be found in [17, 18] (by commercial companies) and [19-21] (by academic research groups).

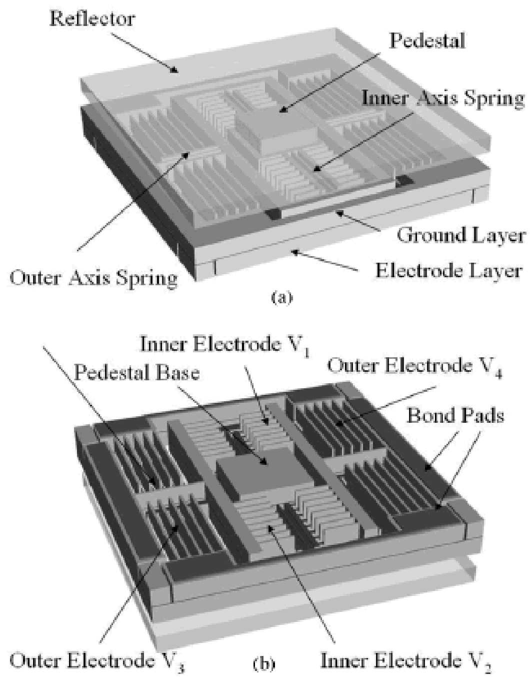

FIGURE 5. Gimbaled micro-mirror design by IW Jung et al.

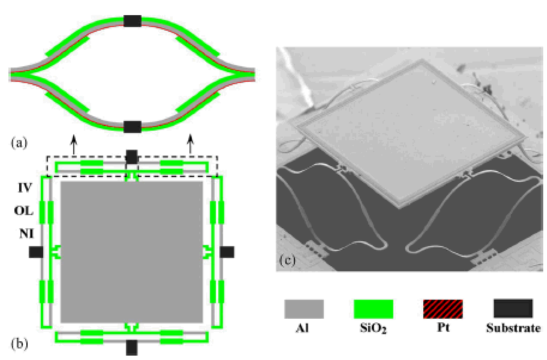

FIGURE 6. Micro-mirror by H. Xie et al.

3) Thermal Discrete Actuation

Electrothermal bimorphs are the most commonly used thermal actuators. Limited by the actuation dynamics, thermally actuated micro-mirrors can only operate at relatively low speed (<100Hz stepping rate), thus less chosen for fast and precise application.

A Thermal Discrete 2D MMA was developed by H. Xie et al. [22] from University of Florida. Figure 6 shows the single mirror design. The mirror surface is suspended by four pairs of electrothermal bimorph actuators. The MMA has an 88% fill-factor, ±15˚ tip/tilt range and ~310um piston range. The response time of the device is on the order of 10ms.

Other Thermal Discrete 2D MMA designs of note can be found in [23] and [24].

4) Lorentz Discrete Actuation

Electromagnetic actuators utilize Lorentz force generated by electric current in magnetic field. The driving torque is controlled by the strength and direction of the current flow. The main challenge in the design of Lorentz Discrete MMAs is current path planning. In addition, Joule losses and disturbance in magnetic field may be issues in practical applications.

Integrated Micro Machines developed a TTP MMA actuated by Lorentz force (Fig. 7a) [25]. The mirror has a 98% fill-factor and can be driven up to ±6˚ tip/tilt and ±50um piston. Position sensors are integrated in the each mirror (Fig. 7b), and a 1kHz closed-loop servo control is achieved. Due to the actuator design, the single mirror size is relatively large (3×3mm^2 and above) comparing to most MMA devices.

Other Lorentz Discrete 2D MMA designs of note can be found in [26] and [27].

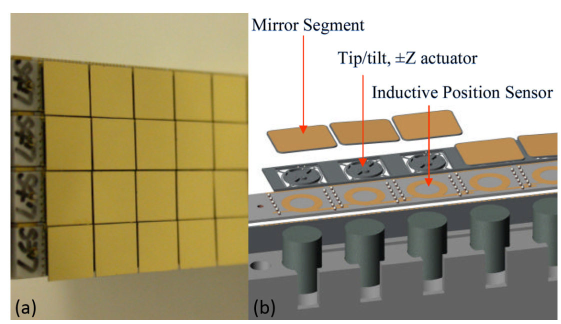

FIGURE 7. Integrated Micro Machines MMA

5) Piezo Discrete Actuation

Piezo actuators are designed to utilize electric-field-induced strain of piezoelectric materials. Typically, piezoelectric materials have large load capacity but small deformation range. Therefore, piezo actuators of discrete 2D MMAs are most commonly in the form of unimorph or bimorph.

There are a few piezo-actuated single micro-mirror designs, but so far there is only one reported 2D MMA with piezoelectric actuation. This MMA is developed by Y. Yee et al. [28]

from LG Electronics Institute of Technology. The 2D TT micro-mirror array is actuated by PZT unimorphs (Fig. 8), achieving ±0.7˚ rotation around outer axis and ±0.5˚ around inner axis.

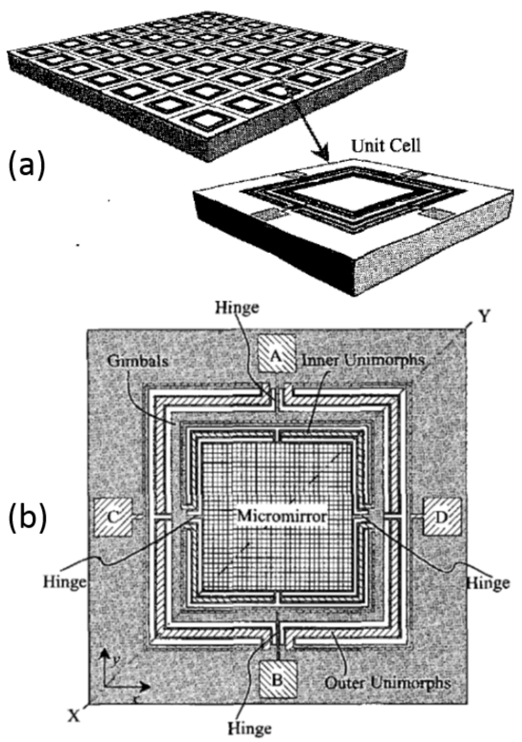

FIGURE 8. MMA Design by Y. Yee et al.

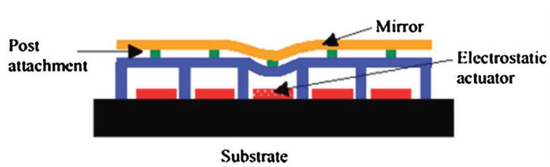

FIGURE 9. Boston Micromachines 4K-DM

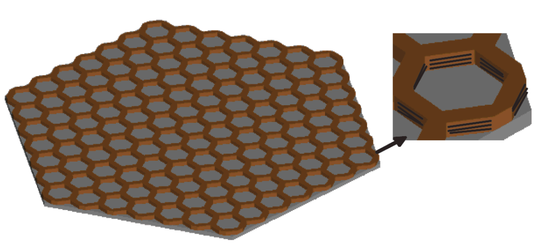

FIGURE 10. Surface Parallel Array DM

6) Plate Continuous Actuation

Boston Micromachines developed a few continuous deformable mirror devices based on same actuator design as TTP-DM [29]. One of them is studied and tested in [30]. Figure 9 shows the basic working principle of this so-called 4K-DM device. It achieves up to 4um of localized deformation within 100us response time. The electrostatic actuators are placed under the mirror surface with a 400um pitch.

IW Jung et al. [31] developed a single-crystal-silicon continuous membrane deformable mirror. The mirror is capable of ~125nm localized deformation with a pitch of 200um at a fast speed (~25kHz).

7) Piezo Continuous Actuation

AOA Xinetics developed a few continuous deformable mirror devices with piezoelectric actuation [32]. In most of their deformable mirror devices, PZT stack actuators are placed directly under the mirror to generate large deformation force on the mirror surface. One exception is Surface Parallel Array, which is actuated by electrostrictive ceramic bimorph actuator array (Fig. 10). The pitch of the actuators ranges from 1mm to 5mm, corresponding to stoke of 0.5um to 4um. The bandwidth varies between 2.5kHz and 5kHz.

8) Lorentz Continuous Actuation

There is only one company named Imagine Optic that developed continuous deformable mirror devices with Lorentz actuation [33]. A typical Imagine Optic deformable mirror achieves ±50 um piston stroke with ~2mm actuator pitch and ~0.5kHz bandwidth.

PERFORMANCE PLOTS

All 2D MMA designs that achieve at least tip and tilt DOFs from among those studies are plotted in Figs. 11 and 12. Figure 11a provides information about the MMA’s dynamic capabilities by showing the maximum angular acceleration against tip/tilt range. The maximum angular acceleration dictates how fast the mirror can be driven. In addition, Fig 11b provides mirror size information by making the scatter dot size proportional to the single mirror size. Figure 12 shows the energy against tip/tilt range.

The green hexagon shown in the figures represents the performance capabilities of a Comb Discrete MMA design created by the authors. This design possesses a transmission feature that enables it to be tuned in such a way that it can be made to slide along the constant energy angled dashed lines in Fig. 11. By comparison, the MMAs with similar or better dynamic capabilities have much smaller single mirror size. The dots corresponding to these MMAs are too small to be seen in Fig. 11b. The thick horizontal dashed line in Fig. 12 represents the theoretical bound on energy density and the thin horizontal dashed line in the same figure represents the practical bound on achievable energy density. The predicted energy density of our design is very close to the practical bound.

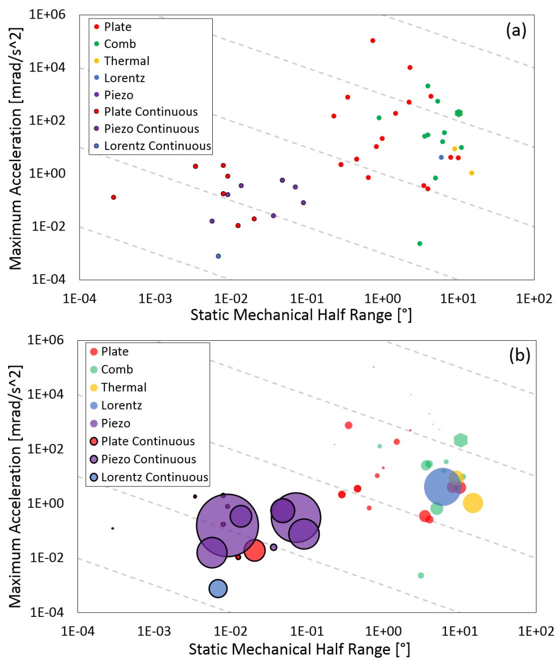

FIGURE 11. Maximum Acceleration vs. Range

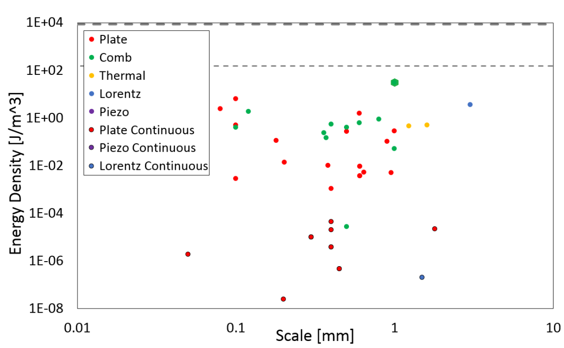

FIGURE 12. Energy Density vs. Size

CONCLUSIONS

The majority of published micro-mirror designs have been studied, categorized, and compared. Plots that capture their performance capabilities have been generated and theoretical bounds have been calculated to help designers recognize how much design improvement is feasible.

This work was performed in part under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-CONF-676358.

REFERENCES

[1] Stewart JB, Bifano TG, Cornelissen S, Bierden P, Levine BM, Cook T. Design and development of a 331-segment tip–tilt–piston mirror array for space-based adaptive optics. Sensors And Actuators A: Physical:230–8.

[2] Tip-Tilt-Piston (TTP)-DM. Boston Micromachines. http://www.bostonmicromachines.com/ttp-dm.htm (accessed August 2015).

[3] Bryzek J, Flannery A, Skurnik D. Integrating microelectromechanical systems with integrated circuits. IEEE Instrum Meas Mag 2004;7.

[4] Bryzek J, Nasiri S, Flannery A, Kwon H, Novack M, Marx D, et al. Very Large Scale Integration of MOEMS Mirrors, MEMS Angular Amplifiers and High-voltage, High-density IC Electronics for Photonic Switching. Nanotechnol. Conf. Trade Show, vol. 1, 2003, p. 300–3.

[5] Yu H, Chen H. Development of a novel micromirror based on surface micromaching technology. Sensors Actuators, A Phys 2006;125:458–62.

[6] Helmbrecht M a, He M, Kempf CJ. Scaling of the Iris AO segmented MEMS DM to larger arrays. Mems Adapt Opt Iii 2009;7209:1–5.

[7] Fernandez A. Modular MEMS design and fabrication for an 80 x 80 transparent optical cross-connect switch. Proc SPIE 2004;5604:208–17.

[8] Chu PB, Brener I, Pu C, Lee SS, Dadap JI, Park S, et al. Design and nonlinear servo control of MEMS mirrors and their performance in a large port-count optical switch. J Microelectromechanical Syst 2005;14:261–73.

[9] Zairi S, Tian GYTGY. Design of buried hinge based 3D torsional micro mirrors. Proc Sixth IEEE CPMT Conf High Density Microsyst Des Packag Compon Fail Anal (HDP '04) 2004:164–70.

[10] Ataman Ç, Lani S, Noell W, Jutzi F, Bayat D, De Rooij N. A dual-axis high fill-factor micromirror array for high thermal loads. Int Conf Opt MEMS Nanophotonics 2011:135–6.

[11] Michalicek MA, Clark N, Comtois JH, Schriner HK. Design and simulation of advanced surface micromachined micromirror devices for telescope adaptive

optics applications. Proc SPIE Vol 3353 Adapt Opt Syst Technol 1998;3353:805–15.
[12] Walton JP, Coutu R a., Starman L. Modeling and simulations of new electrostatically driven, bimorph actuator for high beam steering micromirror deflection angles 2015;9375:93750Y.
[13] Pardo F, Cirelli R a., Ferry EJ, Lai WYC, Klemens FP, Miner JF, et al. Flexible fabrication of large pixel count piston-tip-tilt mirror arrays for fast spatial light modulators. Microelectron Eng 2007;84:1157–61.
[14] Jung IW, Krishnamoorthy U, Solgaard O. High fill-factor two-axis gimbaled tip-tilt-piston micromirror array actuated by self-aligned vertical electrostatic combdrives. J Microelectromechanical Syst 2006;15:563–71.
[15] Panas RM, Hopkins JB. Actuator Design for a High-Speed Large-Range Tip-Tilt-Piston Micromirror Array. Proc ASPE 29th mtg, Boston, MA: Nov 9-14, 2014.
[16] Hopkins JB, Panas RM. Flexure Design for a High-Speed Large-Range Tip-Tilt-Piston Micromirror Array. Proc ASPE 29th mtg, Boston, MA: Nov 9-14, 2014.
[17] Milanoviü V, Matus G a, Mccormick DT, Ave SP, Background a. Tip-Tilt-Piston Actuators for High Fill-Factor Micromirror Arrays 2004:232–7.
[18] Mi X, Soneda H, Okuda H, Tsuboi O, Kouma N, Mizuno Y, et al. A multi-chip directly mounted 512 MEMS mirror array module with hermetically sealed package for large optical cross-connects. IEEE/LEOS Opt MEMS 2005 Int Conf Opt MEMS Their Appl 2005;341:195–6.
[19] Kim M, Park J-H, Jeon J-A, Yoo B-W, Park IH, Kim Y-K. High fill-factor micromirror array using a self-aligned vertical comb drive actuator with two rotational axes. J Micromechanics Microengineering 2009;19:035014.
[20] Tsai J, Chiou S, Hsieh T, Sun C-W, Hah D, Wu MC. Two-axis MEMS scanners with radial vertical combdrive actuators—design, theoretical analysis, and fabrication. J Opt A Pure Appl Opt 2008;10:044006.
[21] Dagel DJ, Cowan WD, Spahn OB, Grossetete GD, Griñe AJ, Shaw MJ, et al. Large-stroke MEMS deformable mirrors for adaptive optics. J Microelectromechanical Syst 2006;15:572–83.
[22] Jia K, Samuelson SR, Xie H. High-fill-factor micromirror array with hidden bimorph actuators and TipTilt-Piston capability. J Microelectromechanical Syst 2011;20:573–82.
[23] Sinclair MJ, Corporation M. 1D and 2D scanning mirrors using thermal buckle-beam actuation 2001;4592:307–14.
[24] Jiang J, Hilleringmann U. Design and fabrication of 2-DOF micromirror array based on electro-thermal actuators. J Beijing Inst Techonology 2006;15:211–5.
[25] O'Hara K. Segmented Galvanometer-Driven Deformable Mirrors. CfAO Presentations: Spring Retreat 2003. http://cfao.ucolick.org/presentations/springretreat2003/integratedmicromachines.pdf (accessed August 2015).
[26] Bernstein JJ, Taylor WP, Brazzle JD, Corcoran CJ, Kirkos G, Odhner JE, et al. Electromagnetically actuated mirror arrays for use in 3-D optical switching applications. J Microelectromechanical Syst 2004;13:526–35.
[27] Cho I-J, Yoon E. A low-voltage three-axis electromagnetically actuated micromirror for fine alignment among optical devices. J Micromechanics Microengineering 2009;19:085007.
[28] Yee Y, Bu JU, Ha M, Choi J, Oh H, Lee S, et al. Fabrication and characterization of a PZT actuated micromirror with two-axis rotational motion for free space optics. Tech Dig MEMS 2001 14th IEEE Int Conf Micro Electro Mech Syst (Cat No01CH37090) 2001;00:317–20.
[29] Standard Deformable Mirrors. Boston Micromachines. http://www.bostonmicromachines.com/production_products.htm
[30] Cornelissen S a., Bierden P a., Bifano TG, Lam C V. 4096-element continuous face-sheet MEMS deformable mirror for high-contrast imaging. J Micro/Nanolithography, MEMS MOEMS 2009;8:031308.
[31] Jung IW, Peter YA, Carr E, Wang JS, Solgaard O. Single-crystal-silicon continuous membrane deformable mirror array for adaptive optics in space-based telescopes. IEEE J Sel Top Quantum Electron 2007;13:162–7.
[32] Wirth A, Cavaco J, Bruno T, Ezzo K, Road J. Deformable Mirror Technologies at AOA Xinetics n.d.;8780:1–12.
[33] DEFORMABLE MIRRORS AND ADAPTIVE OPTIC TOOLS. Imagine Optic

SA. http://www.imagine-optic.com/en/products/deformable-mirrors-and-adaptive-optic-tools/